METHOD AND RECEIVER FOR PROCESSING A MULTI-USER SIGNAL

Field of the Invention

The present invention relates to the field of signal processing for telecommunications, and concerns more specifically multi-user detection ('MUD') and signal processing methods and systems. In particular, it relates to a method and system for detecting and decoding multiple signals which occupy overlapping bandwidth and overlapping time resources. For example, it has application to narrowband mobile satellite communications systems, which use spot beam technology, and where high path loss and limited transmitter power are important factors.

Background

Many efforts have been made in the field of telecommunications to increase the transmission capacity of limited bandwidth, in order to increase the number of simultaneous users able to occupy a common part of the frequency spectrum. In particular, CDMA techniques have been developed, with particular application to wideband radio signals. A number of solutions to the problem of interference suppression have been developed for CDMA systems, including iterative approaches to signal cancellation. This is relatively straightforward, as CDMA systems are inherently interference-resistant, due to the coding employed.

In satellite communications, the re-use of spectrum has been a secondary factor compared with power usage. However, as the number of users increases, an efficient method is needed to distinguish between the different signals. Generally, implementing suitable systems has involved extremely complex solutions and prohibitively high costs. Accordingly, there is a need to overcome the disadvantages of the prior art and provide a new method for decoding multiple channels suitable for use in both narrow and wideband applications, and able to re-use frequency between adjacent spot beams in satellite systems.

Summary of the invention

In a first aspect, the present invention provides a method for processing a multi-user signal, the method comprising an iterative receiver process including the steps of:

(a) receiving a signal transmission including a plurality of user signals on a TDMA channel;

The invention, then, has particular application in narrowband TDMA with reservation/channel assignment procedures or random access techniques (eg: ALOHA), in satellite line-of-sight propagation environments, and in power limited systems.

The system of the invention can operate with arbitrary waveforms (in narrow or wideband). Unlike known narrow band multi-user systems, interference suppression is accomplished via the canceller, rather than using different channel interleavers. In addition, the invention employs iterative cancellation of partially overlapping signals with identical reference sequences (e.g. unique words - UW).

Preferably, the method further comprises the step of either continuing further steps or producing a hard signal for the first user and discontinuing further steps depending on the application of receiver convergence criteria to the decoded probabilities.

During the first iteration of the iterative receiver process, the decoder convergence criteria may include comparing the interference on the detected user signal for the first user with an interference threshold determined by estimating the noise equivalence of interference on the detected user signal due to other user signals, with the probabilities being fully decoded if the interference is below the interference threshold or partially decoded if the interference is above the interference threshold.

The decoder convergence criteria may also include adaptively adjusting a threshold of a stopping criteria, a probability being fully decoded when the application of the stopping criteria to a probability results in a value less than the threshold and partially decoded when the application of the stopping criteria results in a value greater than the threshold.

Preferably, the stopping criteria utilises the refined probabilities from a previous iteration of the iterative decoding algorithm. The stopping criteria may for example be the sign change ratio stopping criteria.

Alternatively, the decoder convergence criteria utilises a stored value of the optimal number of iterations of the iterative decoding algorithm for any particular iteration of the iterative receiver process. The stored values may, for example be calculated from investigation of the convergence behaviour of the iterative decoding algorithm and/or the iterative receiver process. Preferably, the investigation includes analysing the exchange of mutual information between the output of step (c) and step (e) during an offline simulation of the iterative receiver process.

Preferably, the receiver further comprises means for producing a hard signal for the first user and discontinuing the iterative receiver process depending on the application of receiver convergence criteria to the decoded probabilities.

During the first iteration of the iterative receiver process, the decoder convergence criteria typically includes comparing the interference on the detected user signal for the first user with an interference threshold determined by estimating the noise equivalence of interference on the detected user signal due to other user signals, with the probabilities being fully decoded if the interference is below the interference threshold or partially decoded if the interference is above the interference threshold.

The decoder convergence criteria may also include adaptively adjusting a threshold of a stopping criteria, a probability being fully decoded when the application of the stopping criteria to a probability results in a value less than the threshold and partially decoded when the application of the stopping criteria results in a value greater than the threshold.

For example, the stopping criteria, may utilise the refined probabilities from a previous iteration of the iterative decoding algorithm.

Optionally, the stopping criteria is the sign change ratio stopping criteria.

Alternatively, the decoder convergence criteria utilises a stored value of the optimal number of iterations of the iterative decoding algorithm for any particular iteration of the iterative receiver process. The stored values may be calculated from investigation of the convergence behaviour of the iterative decoding algorithm and/or the iterative receiver process. This investigation may include analysing the exchange of mutual information between the output of the interference canceller and the iterative decoding algorithm during an offline simulation of the iterative receiver process.

Typically, the receiver includes a plurality of calculating means and digital signal processors for the parallel refining and decoding of a posteriori probabilities for each of the plurality of users detected by the detector.

The receiver may also include a channel estimator for providing updated channel estimates for each user and combining the updated channel estimates with the refined probabilities to form the weighted representations of user signals used in a subsequent iteration of the iterative receiver process.

To illustrate the invention and how it may be put into effect, reference will now be made to the accompanying drawings, which represent a preferred non-limiting embodiment. In the drawings:

Figure 1 diagrammatically illustrates a narrowband multi-user signal receiver;

Figure 2 illustrates an exemplary iterative architecture and adaptive control of the receiver illustrated in Figure 1;

Figure 3 depicts a schematic illustration of an exemplary interference canceller from the receiver illustrated in Figure 2;

Figure 4A shows a flow chart depicting the multi-user signal processing method of the invention utilising the noise equivalence of interference due to other user signals as convergence criteria;

Figure 4B shows a flow chart depicting the preferred embodiment of the multi-user signal processing method of the invention utilising convergence criteria including Sign Change Ratio and values from a look up table; and

Figure 5 illustrates an EXIT chart from which values of the look up table shown in Figure 4B may be derived.

Detailed description of the drawings

In this specification, unless the context otherwise provides, the following terms are used with the following definitions:

'convergence' – implies an iterative algorithm has reached a locally stable value;

'partial decoding' – employing an optimal number of iterations (as decided by application of suitable criteria) with respect to convergence and complexity for an iterative decoding algorithm, for a particular iteration of a multi user receiver;

'fully decoding' – employing a number of iterations to provide the best estimate of a value calculated by an iterative decoding algorithm.

Further, in this specification, where a document, act or item of knowledge is referred to or discussed, this reference or discussion is not an admission that the document, act or item of knowledge or any combination thereof was at the priority date part of common

In general, this has complexity that increases exponentially with both the number of users and the codeword length. For convolutionally encoded data, joint decoding corresponds to Viterbi decoding on a super-trellis whose states are the concatenations of the individual user states. Optimal decoding is therefore feasible for only a very small number of users. Furthermore, in the case where turbo codes are used, the required super-trellis becomes too cumbersome to be practical. The concept of optimal decoding is, however, useful in providing a benchmark against which other methods may be measured.

Interference Cancellation

With careful selection of the users' code rates, or equivalently, their transmit power, successive cancellation of decoded data streams can approach the performance of the optimal decoder. In order for this scheme to be practical, however, the users' powers must be tightly controlled. Thus, interference cancellation is better suited to situations where power control can be implemented.

Joint Detection, Independent Decoding

Because of the high complexity of optimal joint detection, it is necessary to try to design sub-optimal receivers with lower complexity. The key trade-off is performance versus complexity. One approach to reducing complexity is to separate the problems of detection and decoding. The receiver of the invention makes joint decisions on each received signal (ignoring the constraints due to coding). The resulting signal streams are then independently decoded . Such a strategy results in minimal change to existing architectures.

Multistage Detection

Multi-stage detectors use a process of successive cancellation of the uncoded bits. Cancellation can proceed in serial or parallel. Multistage detectors can be classified as linear or non-linear, according to whether they subtract linear or non-linear functions of the already detected symbols.

Iterative Decoding

The preferred embodiment of the present invention implements a class of sub-optimal iterative non-linear decoding strategies. The high complexity of optimal decoding arises mainly from the fact that the constraints introduced by coding and channel effects must be processed jointly for all users. In contrast, iterative non-linear methods aim to iteratively reconstruct from the channel output each user's transmitted waveform using

burst. One embodiment of the present invention carries out channel estimation on a packet-by-packet basis, for each iteration, and using a reference sequence (eg a UW) present in the packet. This updating of the channel estimation on each pass, if neccesary, can lead to significant improvement in receiver performance.

Iterative Multi-User Decoding

We now focus on the multi-user receiver architecture according to the present invention. The architecture is flexible enough to provide a range of solutions of different complexity for different applications. Furthermore, there are a number of optional features that can be incorporated, depending upon the changes permitted to the system requirements.

Broadly speaking, the system of the invention achieves interference suppression by first detecting and decoding the received signals in multiple stages, and then cancelling the unwanted signals. This process is carried out iteratively, and this approach has application to interferers that are asynchronous to the wanted signal.

Figure 2 shows an exemplary architecture of a receiver 200 suitable for decoding multiple users, signals $y_1, y_2, \ldots y_k$, in accordance with the present invention. Performance tests have shown this architecture to yield near optimal performance (approaching single user) under certain conditions and linear increase in complexity with increasing numbers of users. The architecture consists of a feedback structure comprising an interference canceller 201, channel estimator 202, soft demodulator 204A-204C, soft output decoder 206A-206C, soft modulator 208A-208C and estimated multi-user channel apparatus 210.

The receiver 200 comprises multiple parallel processor arms as shown, each receiver arm serving to converge on a respective user (see below). Each component of the receiver can be constructed using existing hardware, as will be understood by those skilled in the art. In particular, decoders 206A-206C comprise digital signal processing hardware suitable for running an iterative decoding algorithm. Broadly, the principle of operation is to iteratively improve soft estimates of multiple users simultaneously, where the users' signals occupy overlapping channel time/bandwidth resources. With no a priori knowledge of users, the number of active receiver arms can vary through successive iterations, as weaker signals become apparent through progressive interference suppression (and the architecture then includes a further receiver arm).

cancelling module is a non-linear cancellation device where the soft estimate $x^{\wedge}_k[i]$ of the coded and modulated symbol for user k is obtained by subtracting from $y[i]$ the average contribution of other users (where the average is calculated according to the posterior distributions from the previous iteration). Note that in order to cancel each user's contribution to the received vector, estimates of the users' channels are required.

Prior approaches to iterative signal estimation approaches have employed processing steps such as hyperbolic tangent devices, which are used to control how much of the estimated interference is actually used in the cancellation at each iteration. Such methods require an estimation of absolute power to be made at the antenna, as without such prior knowledge the algorithm may be ineffective. In contrast, in the present invention, this soft decision step is implemented by way of the non-linear device described. In this approach to the weighting, the sum of the candidate bit probabilities is equal to one. This contrasts with a device such as the hyperbolic tangent device referred to above, wherein this sum total is artificially reduced to compensate for the inaccuracy of the estimated signal. As the method of the invention does not involve locking into the signal on initial receiver iterations, it is not required to compensate for initial inaccuracies.

The operation of the canceller 201 is as follows:

Field $y_1, y_2, \ldots, y_K$ are received signals

$$R_p = \sum_{i=1:K\backslash i\neq p} \rho_{pi}\hat{z}_i$$

$p = 1, 2, \ldots, K$
z_i is the output of the i^{th} soft modulator after reapplying the channel parameters.
ρ_{pi} – relative interference value of the i^{th} user interfering with user p.

$$\hat{x}_p = y_p - R_p$$

Thus, the exemplary embodiment depicted in the figures involves an iterative multi-user device for multi-user decoding for narrow-band satellite services. The general structure of the components of the receiver illustrated in Figures 2 and 3 will now be described in further detail

The vector channel output $y[i]$ from the estimated multi-user channel apparatus 210 is processed in subsequent iterations by the following devices:

At each iteration, the control settings to be applied in setting the threshold are updated. Alternatively, the adaptive behaviour may be determined by experimental optimisation through pseudo-analytical methods (statistical techniques – see below) such as 'EXIT' (EXtrinsic Information Transfer) Chart analysis or mutual information transfer chart analysis. Another alternative is to apply stopping criteria, such as a sign change ratio criteria (see below).

4. **Soft turbo decoder:** Refines the a-posteriori probabilities of the coded bits by taking into account the knowledge of the turbo code. As noted above the signals are only partially decoded during the first few receiver iterations in order to prevent the estimated signal from locking in to an incorrect value (ie converging to a false lock, an incorrect codeword nearest the transmitted signal - plus noise, plus interference).

5. **Soft modulator:** The soft modulator 208A-208C produces the conditional expectation $E[x_k[i]]$ of the coded and modulated symbols (according to the posteriors calculated by the decoders). These average symbols are further fed back to the multi-user detector for the next iteration.

6. **Channel estimator:** The channel estimator 202 updates the channel estimate for each user. Note that this device takes as input the output of the interference canceller 201 and feeds each user's signal parameters to the estimated multi-user channel 210 and the interference canceller 201. This shows that the channel estimator is one of the key points for convergence of such an iterative system. Note that if enough training symbols are present, or at high enough signal to noise ratios, the channel estimates from the initial iteration may be sufficiently accurate.

With reference to Figure 4A and 4B (in which the same reference numerals have been used to refer to directly equivalent steps) the operation of the multi user detection method of the invention is illustrated, employing alternative convergence criteria. In the method of Figure 4A, a signal transmission is received (400) at the receiver, the signal including a plurality of user signals. A test is performed (401) as to whether it is the first iteration or not. If not, estimates of other user signals are cancelled (403) from the signal of the first user. On the first iteration there are no estimates of other users available so the canceller does not operate. On subsequent iterations a weighted representation of the other user signals is subtracted from the signal of each user of interest and a soft signal is thus produced.

a lookup table. A further convergence criteria includes the application of a stopping criteria such as the sign change ratio stopping criteria, described further below.

The signals are decoded (412) by iterating the decoding algorithm through the number of iterations (as determined at 414) or until application of the stopping criteria shows that convergence has occurred. In either case, the adaptive controller will set the threshold for the stopping criteria or deliver the relevant number of iterations to either partially or fully decode a user.

User convergence is determined (416) and where all users are fully decoded (418) a hard signal is output (420) and no further processing occurs. Alternatively the decoded signal is modulated (422) and pulse shaped (424) and a subsequent iteration is commenced (from 402).

It will thus be realised that the adaptive controller controls the decoding process to ensure convergence with minimum complexity on any particular iteration of the iterative receiver process. The behaviour of the decoder under different conditions can be investigated to arrive at a decoder profile. Several profiles can be computed offline for different scenarios of number of users and relative interference, as schematically represented in Figure 4A and 4B by the pseudo-analytic convergence verification process (421, 426). In actual operation the receiver can then identify the closest scenario and employs the appropriate partial decoder profile. This approach of storing the optimal number of decoder iterations for any particular iteration of the multi user detection method operates as a pseudo-analytical tool – a 'look-up' table (LUT) (410) – to decide at each receiver iteration the partial decoding required.

Convergence behaviour can be investigated by EXIT chart analysis, which is discussed further in 'Convergence Behavior of Iteratively Decoded Parallel Concatenated Codes'; Stephan ten-Brink; IEEE Transactions on Communications; Vol. 49, No. 10; pp 1727; October 2001, which is incorporated by reference in its entirety. The EXIT chart analysis can be viewed as a software gauge attached to the soft outputs of the decoder, enabling determination of convergence by determining the number of turbo iterations.

Convergence behaviour may also be investigated by making on-line measurements of the decoder output. There is, of course, a trade-off between complexity and performance of the different techniques. In the case of the LUT method, the average behaviour of the MUD system described is investigated off-line via the EXIT Chart analysis tool. Mutual information

criterion' method. Once the sign change ratio SCR (number of sign changes divided by the packet length) falls below the threshold, the turbo decoding iterative process can be terminated with minimal degradation; the threshold is determined from simulations and set by the adaptive controller The smaller the threshold, the smaller the amount of BER degradation. This method can be used for turbo decoder iteration control, but is also used to control MUD iteration, based on the final information bit estimates output by the turbo decoder after *N* iterations.

In MUD controller mode, the sign change metric is used to determine when to cease subsequent decoder visits for the user of interest. The function is called once at the end of each MUD iteration. For each user the metric is checked according to the sign change metric stop criterion. If stop conditions are met for any user a value of 0 is returned and no further MUD iterations are performed for this user. It is to be noted that this does not prevent other users from continuing to iterate as appropriate. The receiver uses a combination of the LUT and SCR approaches to provide the best performance for the least complexity.

The convergence properties of the method of the present invention have been analysed by the inventors. This analysis has showed that the receiver architecture, when combined with appropriate probabilistic component algorithms, allows very high spectral efficiencies to be achieved. Experiments have suggested spectral efficiency up to approximately 10 bits per second per Hertz *(bps/Hz)*, compared with conventional transmitter receivers that achieve 1-2 *bps/Hz*, with only a small increase in transmitter power (less than 1dB). Studies of the effects of the system of the invention on acquisition and decoder performance have demonstrated that this approach provides particular advantages when acquiring a weak user signal in the presence of a much stronger interfering signal.

The technique described above involves the strongest users (signal) on each arm of the receiver being detected, and other interfering users cancelled from it with the appropriate weighting. Each user's signal is therefore taken from only one detector arm, this approach being referred to as 'selective combining'. It is to be noted that the invention can also be applied to other post-detection combining techniques such as 'maximal ratio combining', where the contributions from each user are combined for each of the receiver arms. Combining techniques are further described in "Mobile Communications Engineering, Theory and Applications", W. C. Y. Lee, McGraw Hill, 1997, which is incorporated by reference in its entirety.